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MODEL-BASED DEVELOPMENT OF DESIGN PROCESS MODELS

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Abstract. Not only do generic compositional models of design support the analysis of design processes and the development of practical design support systems, they also provide the basic structure for more specific design process models. The generic design model GDM provides a compositional structure that has been refined for different types of design as illustrated in this paper for a number of practical design applications. These new models have proven to be applicable in different domains.

1. Introduction

A design process, in general, involves not only the construction of a description of an artefact, but also the determination of (additional or substitute) requirements of the artefact, and the strategic co-ordination of these activities. In order to thoroughly analyse a design process, or to develop a support system for a design process, a model is indispensable. To develop a model for a specific design process, one of two strategies can be chosen: generate a design process model from scratch, or apply/modify an existing design process model. The second is often only more efficient if a generic model exists with structures that are applicable to the specific design process.

The generic design model GDM developed by the AI Department of the Vrije Universiteit Amsterdam provides a compositional structure that can be specialised to develop models for a wide range of design processes in terms of their process structures, knowledge structures, and the relationship between these structures (Brazier, Langen and Treur, 1998).

This paper presents a number of more specific models, based on GDM, supported by examples of our research on practical design applications.

This paper is organised as follows. Section 2 briefly describes research on the development and use of design process models. Section 3 presents the main features of GDM, and Section 4 gives examples of design processes that have been modelled as specialisations of GDM. Section 5 ends with a discussion.

2. Research on design process models

Most often, research on design process models focuses on specific design methods or design principles. A *design method* is a normative description of how to represent design problems and solutions as well as how to design in a specific application domain (Pahl and Beitz, 1984; French, 1985; Maher, 1990; Bernaras and Van de Velde, 1994; Blessing, 1994; Smithers, 1996). The norms on which a design method is based usually come down to a few design principles. A *design principle* is an invariant for a design process, such as to maintain the independence of requirements or to minimise the amount of information included by the design solution (Asimow, 1962; Pahl and Beitz, 1984; French, 1985; Goel and Pirolli, 1989; Pugh, 1990; Suh, 1990).

According to most design researchers, a design method should contain the following representations: design problem space representation, design solution space representation, design knowledge representation, and design prototype.

A *design problem space representation* is a representation of a space of design problems (Tong, 1987; Brown and Chandrasekaran, 1989; Chandrasekaran, 1990; Zhao and Maher, 1992; Bernaras and Van de Velde, 1994; Löckenhoff and Messer, 1994; Runkel, Balkany and Birmingham, 1994; Wielinga and Schreiber, 1997).

A *design solution space representation* is a representation of a space of design solutions (Tong, 1987; Brown and Chandrasekaran, 1989; Chandrasekaran, 1990; Zhao and Maher, 1992; Bernaras and Van de Velde, 1994; Runkel, Balkany and Birmingham, 1994; Löckenhoff and Messer, 1994; Wielinga and Schreiber, 1997).

A *design knowledge representation* is a representation of process control knowledge (i.e., control flow in a design process), search control knowledge (e.g., propose-and-revise and constraint satisfaction) and application domain knowledge (Tong, 1987; Goel and Chandrasekaran, 1989; Brown and Chandrasekaran, 1989; Chandrasekaran, 1990; Zhao and Maher, 1992; Bernaras and Van de Velde, 1994; Löckenhoff and

Messer, 1994; Runkel, Balkany, and Birmingham, 1994; Wielinga and Schreiber, 1997; Clarkson, Melo, and Connor, 2000).

These three types of representations may be combined into a *design prototype*, which organises knowledge about a set of similar design situations and which forms a framework for studying design processes (Koller, 1985; Tong, 1987; Coyne, Rosenman, Radford, Balachandran, and Gero, 1990; Gero, 1990; Zhao and Maher, 1992).

3. Generic Design Model GDM

The Generic Design Model GDM has been developed using the compositional design method DESIRE for the structured design of autonomous, interactive, compositional systems (Brazier, Jonker and Treur, 2002). Compositionality is a general principle that refers to structuring a system from a component-based perspective. The design method DESIRE structures both processes and knowledge in a compositional manner. Compositionality is a means to achieve *information* and *process hiding* within a model: by defining processes and knowledge at different levels of abstraction, unnecessary details can be hidden.

A generic model is usually not invented from scratch, but the result of a (possibly long) process of empirically studying practical applications, investigating related research and many (partially successful) design efforts. Conceptual analysis of process characteristics is the main rationale for the components distinguished in a generic model, in order to abstract from the details from specific domains of applications and process methods.

GDM is a blueprint of the generic features of design processes: GDM models the essential types of information and knowledge that play a role within a design process, irrespective of application domains and design methods. The components in GDM have been distinguished in design processes in different application domains, such as those presented in Section 4. Generic structures were extracted from these example models and combined, leaving out domain-specific elements. For a preliminary version, see (Brazier, Langen, Ruttkay, and Treur, 1994), for a more detailed treatment of strategic knowledge at different levels, see (Brazier, Langen, and Treur, 1998).

A design process, as a whole, generates a design object description that fulfils a specific set of qualified design requirements while adhering to design process objectives. Figure 1 shows the processes and information links involved.

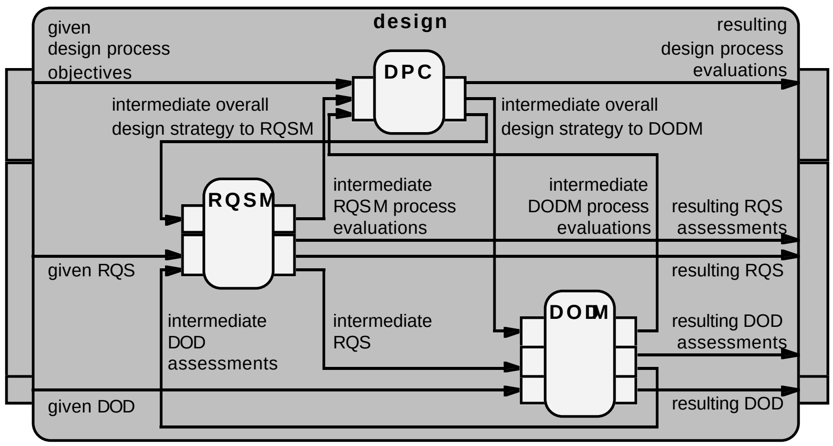

Figure 1. Processes and information links within design as a whole.

A *design process co-ordination process (DPC)* controls a design process in accordance with given design process objectives, by imposing an overall design strategy on the requirement qualification set manipulation process and the design object description manipulation process that are part of the design process.

On the basis of a given requirement qualification set, and in interaction with stake-holders (such as a client), a *requirement qualification set manipulation process (RQSM)* aims to generate a well-structured requirement qualification set (RQS) that includes sufficient design requirement information for the generation of a satisfactory design object description. This process always operates on one (possibly partial) set of design requirements called the current requirement qualification set.

During a requirement qualification set manipulation process, the contents of the current requirement qualification set may vary due to the addition, modification, or deletion of design requirement information. Figure 2 shows the processes and information links within a requirement qualification set manipulation process.

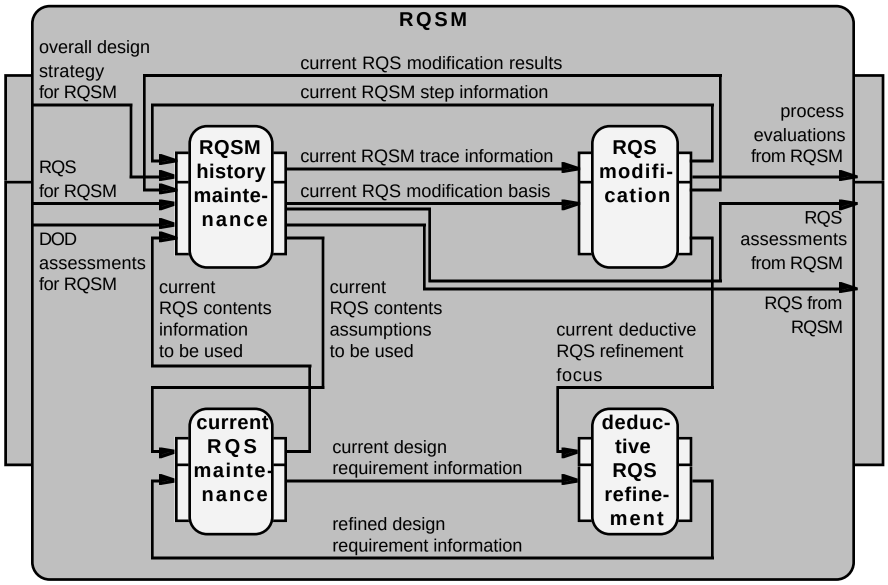

Figure 2. Processes and information links within requirement qualification set manipulation.

A *design object description manipulation process (DODM)* aims to generate a consistent design object description (DOD) that fulfils a given requirement qualification set and that includes sufficient domain object information for the intended use of the design object description. (The intended use of a design object description is to be the basis for the assembly, construction, fabrication or another form of implementation of the design object.) This process always operates on one (possibly partial) description, called the current design object description.

During a design object description manipulation process, the contents of the current design object description may vary due to the addition, modification, or deletion of domain object information. The processes and information links within a design object description manipulation process are similar to those shown in Figure 2.

4. Design process models as specialisations of GDM

A generic model provides a frame of reference for the development of new models. Ideally, most parts of the generic model (i.e., components, information types, information links, task control, and knowledge bases) can be identified, those parts that can not are modified or removed, and application specific and domain specific process structures (components), knowledge structures and information links are added/modified. GDM as described above in section 3 has been used to model design processes in different domains of application (and thus empirically tested). New, more detailed models for specific sub-processes are the result. This section presents two design process models developed on the basis of specialisations of GDM.

One of the design process models obtained by specialisation of GDM is based on viewing a modification process as a form of process control. From this viewpoint, the following processes can be distinguished at the two highest levels of process abstraction of an RQS modification process:

- *RQS modification* as a whole,
- *RQS modification analysis*, which assesses the current requirement qualification set and which evaluates the current state of the requirement qualification set manipulation process, and
- *RQS modification determination*, which determines the course of action to be taken (i.e., modification of the current requirement qualification set, termination of the requirement qualification set manipulation process, retrieval of an earlier generated requirement qualification set, deductive refinement of the current requirement qualification set, or inspection of the requirement qualification set manipulation history).

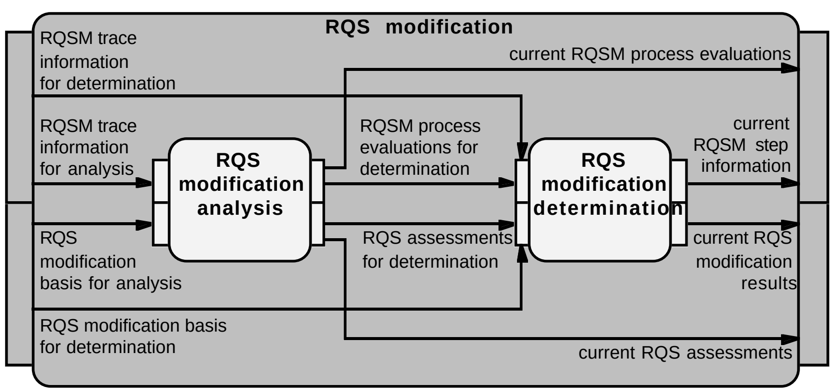

Figure 3. Processes and information links within RQS modification.

The following processes are involved at the two highest levels of process abstraction of an RQS modification analysis process:

- *RQS modification analysis* as a whole,
- *RQS assessment*, which assesses the current requirement qualification set (with respect to the satisfaction of the design requirements it includes as well as its fulfilment),

- *RQS modification evaluation*, which evaluates the effects of the most recent set of modifications that led to the current requirement qualification set,
- *RQSM process evaluation*, which evaluates the requirement qualification set manipulation process (up to its current state) against the current overall design strategy.

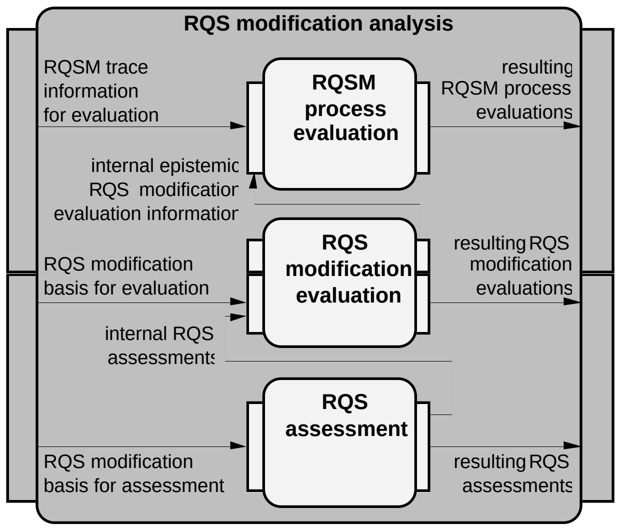

Figure 4. Processes and information links within RQS modification analysis.

The specialisation for RQS modification determination is based on the "object-act" paradigm of first selecting an object and then determining an action to be performed on that object. (The "object-act" paradigm is the basis of object oriented modelling, design and development.) According to this specialisation, the following processes are involved at the two highest levels of process abstraction of RQS modification determination:

- *RQS modification determination* as a whole,
- *RQS modification focus determination*, which determines the part of the current requirement qualification set for which a modification is to be determined next,
- *RQS modification method determination*, which determines the method by means of which a modification to the current focus is to be determined next,
- *RQS modification method execution*, which executes the current method in order to determine a modification to the current focus.

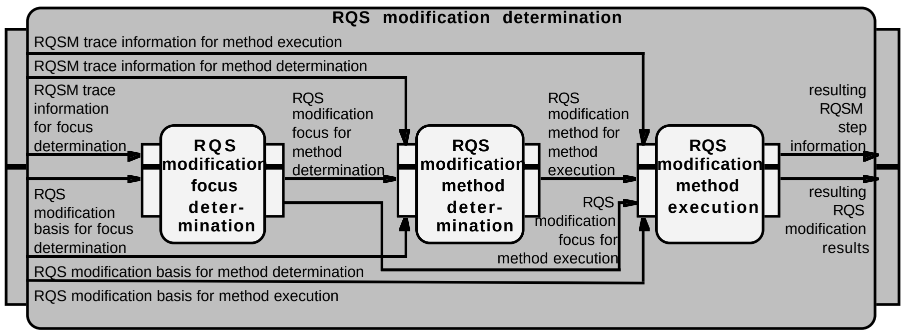

Figure 5. Processes and information links within RQS modification determination.

Similar specialisations of the DOD modification component are not described in detail here, for reasons of space limitation.

The specialisation of RQS modification into an RQS modification analysis process and an RQS modification determination process has been used, among others, to model conflict management within a design process (Brazier, Langen and Treur, 1995). For example, an RQS modification determination process resolves a design conflict related to the current requirement qualification set by selecting an alteration to this set that deletes or modifies design requirements involved in the conflict.

The same specialisation has been used as part of a model of the generation and re-use of design rationale within a design process (Brazier, Langen, and Treur, 1997). In the context of an aircraft re-design example, an RQS modification analysis process determines which (pairs of) requirements of the aircraft are in conflict with each other, and which requirements have to be refined further.

The specialisation of DOD modification into a DOD modification analysis process and a DOD modification determination process has been applied, among others, to elevator configuration (VT), where the design object to be configured is an elevator, and the design requirements consist of customer specifications, building dimensions and constraints (Brazier, Langen, Treur, Wijngaards and Willems, 1996). The DOD modification analysis process analyses the results of modifying the current elevator configuration: it determines whether the last modification has resulted in a complete configuration that does not violate any constraints and, if the previous configuration violated a constraint, whether the last modification fixed that constraint violation without introducing new violations. Furthermore, the DOD modification determination process proposes initial or revised parts and values of parameters of an elevator configuration.

The same specialisation has been re-used to develop a model of environmental inventory, where the object to be designed is a model of a specific industrial process, on the basis of which the environmental impact of this process is derived (Langen, Brazier, Diepenmaat, and Pulles, 1995). The design requirements are conditions on the quality of the environmental impact information about this industrial process. In environmental inventory, the DOD modification analysis process analyses the results of modifying the current model of the industrial process: it determines whether the last modification has not resulted in a degradation of the quality of the environmental impact information about the industrial process of concern. Furthermore, the DOD modification determination process proposes initial or revised values of parameters of the industrial process model.

5. Discussion

This paper shows how the analysis of design processes and the development of practical design support systems can be supported by using a generic model as a point of departure. The generic design model GDM can be specialised to obtain new, specific design process models, which are applicable in different domains.

Often a trade-off has to be made on the amount of support that a generic model and/or its specialisations will provide. On the one hand, the more structures, the more support is given. On the other hand, the richer the structure, the more restrictive its scope of application.

Future research is directed towards developing a library of specialised models, creating ontologies for design process structures and knowledge structures, finding and matching models within such as library, and automated design and re-design of more specific models.

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